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Spatial Temporal Processing in TD-SCDMA

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Terms and Acronyms

Term	Definition
CDMA	Code Division Multiple Access
JD	Joint Detection
TD-SCDMA	Time Division Synchronous CDMA
UMTS	Universal Mobile Telecommunications System
Mcps	Mega Chip Per Second

1. Introduction

1.1. Scope and Audience

This paper presents details of the spatial-temporal processing of a received TD-SCDMA signal and its channel impulse response.

This document is targeted at systems engineers who are designing TD-SCDMA systems who are interested in deploying the Motorola MRC6011 in their designs. It is also targeted to applications engineers and marketing professions who want to learn more about the broad range of applications of the Motorola RCF technology.

1.2. Executive Summary

CDMA based systems suffer from Multiple Access Interference (MAI) and it affects all users equally. FDD based systems attempt to deal with the problem by using detection schemes such as the rake receiver, however these schemes are sub-optimal because they only consider one user's signal information and do not take into account the interference from all other users in the system.

Joint Detection algorithms on the other hand are designed to process all users in parallel by including the interference information from the other users. In general Joint Detection schemes are complex and computationally intensive (complexity grows exponentially as the number of users increases) because most of the operations are matrix and vector based operations, as the number of the users increase, the sizes of the matrices and vectors increases and therefore the computation power that is required to separate the users.

TD-SCDMA however, solves this problem by limiting the number of users in a given time slot to 16, this creates a very manageable number of users that need to be processed in parallel, furthermore these users are also synchronized.

1.3. Background

In the year 1998 the Chinese Wireless Telecommunications Standards (CWTS, http://www.cwts.org) put forth a proposal to the International Communications Union (ITU) based on TDD and Synchronous CDMA technology (TD-SCDMA) for TDD. This proposal was accepted and approved by the ITU and became part of 3GPP in March of 2001.

TD-SCDMA was incorporated as part of the TDD mode of operation in addition to the existing TDD-CDMA mode of operation. To accommodate both modes, 3GPP now includes a "low chip rate" mode of 1.28 Mcps that corresponds to the TD-SCDMA specifications. Because of this TD-SCDMA is sometimes referred to as the low-chip rate mode of UTRA TDD.

Table 1-1 shows where TD-SCDMA fits in relationship to other 3GPP standards

3GPP		
Name	**Access Mode**	**Chip Rate**
WCDMA	FDD	3.84 Mcps
TDD-CDMA	TDD	3.84 Mcps
TD-SCDMA	TDD	1.28 Mcps

Table 1-1 TD-SCDMA in relationship to other 3G standards

2. Signal Model

2.1. TDD/TDMA

Internet based applications, media (audio and video) enabled applications and file transfers have very different bandwidth requirements for uplink and downlink traffic. TD-SCDMA does not dictate a fixed utilization of the frequency band; rather uplink and downlink resources are assigned according to traffic needs.

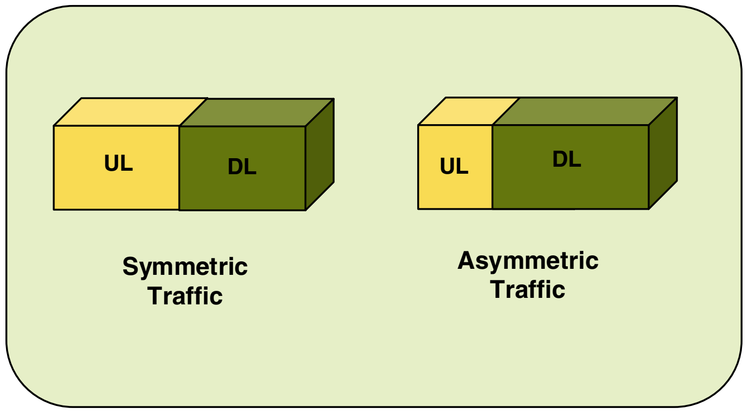


Figure 2-1 Symmetric and Asymmetric traffic support in TD-SCDMA

The variable allocation of the time slots for uplink or downlink traffic is what allows TD-SCDMA to efficiently support asymmetric traffic requirements and a variety of users. Figure 2-1 illustrates this principle where for symmetric traffic, the time slots are equally split and for asymmetric traffic the DL can use more time slots.

2.2. TD-SCDMA Frame Hierarchy

TD-SCDMA uses both unique codes and time signatures to separate the users in a given cell. The standard defines a very specific frame structure as shown in Figure 2-2. There are three different layers: the radio frame, the sub-frame and the individual time slots. Depending on the resource allocation, the configuration of the radio frames becomes different. The radio frame is 10ms; the sub-frame is 5 ms in length and is divided into 7 slots. The standard also specifies various ratios for the number of slots between these two groups in order to meet specific traffic requirements. All physical channels require a guard symbol in every time slot.

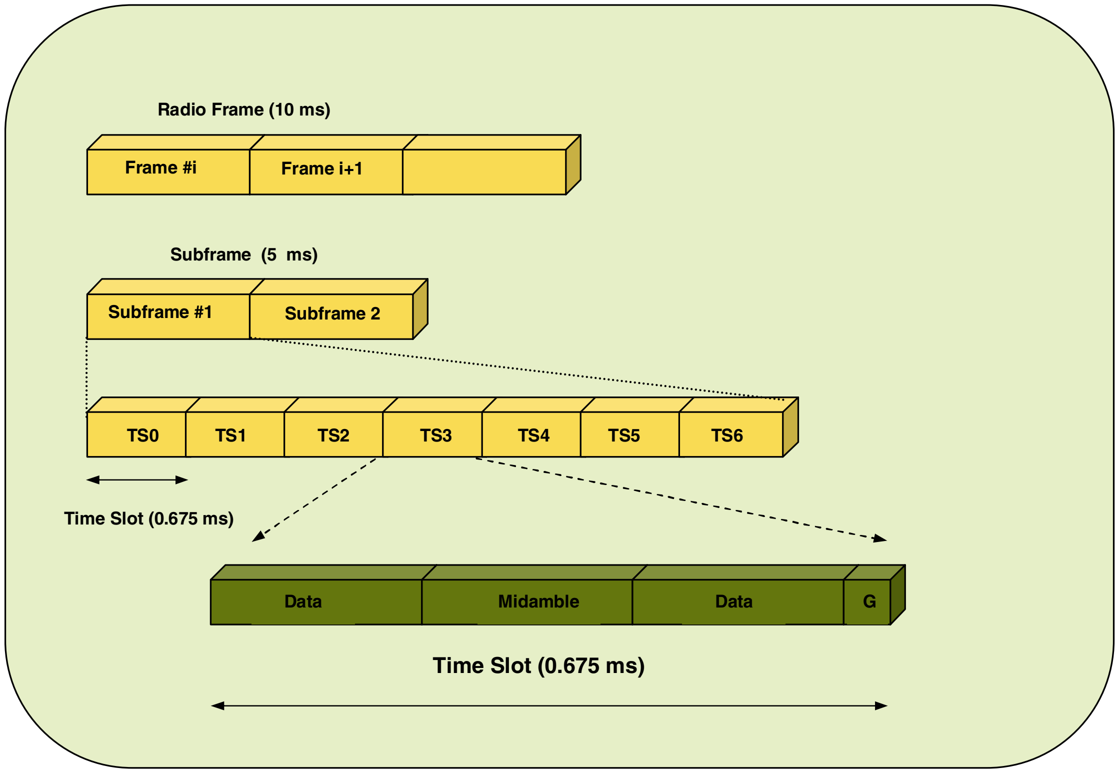


Figure 2-2 TD-SCDMA Frame Structure

2.3. TD-SCDMA Slot Structure

A TD-SCDMA time slot has been designed to fit into exactly one burst. The time slot (Figure 2-3) consists of four parts, a *midamble* with 144 chips duration, and two identical data fields with 352 chips duration at each side of the midamble and followed by a 16 chips guard period. The midamble is used by the receiver to carry out channel estimation tasks.

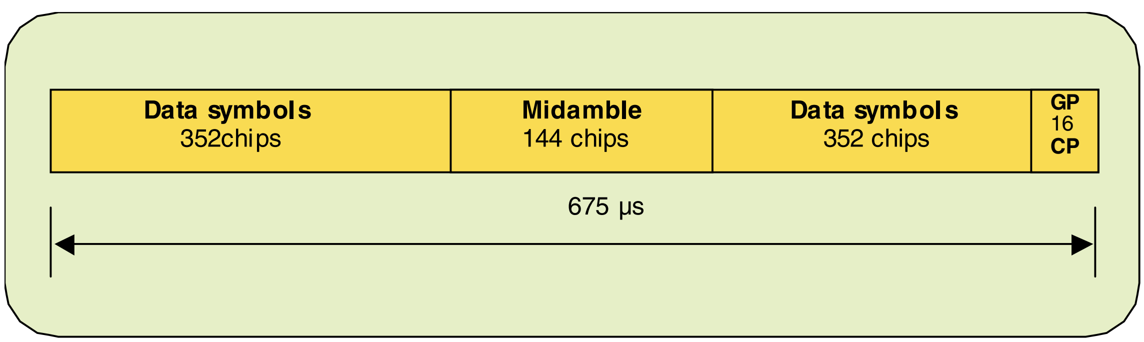


Figure 2-3 The TD-SCDMA Slot Structure

3. System Model

3.1. Channel Model

In a TD-SCDMA system, we have K users who access the channel simultaneously. On the same frequency and in the same time slot. Figure 3-1 shows a general model of a TD-SCDMA System.

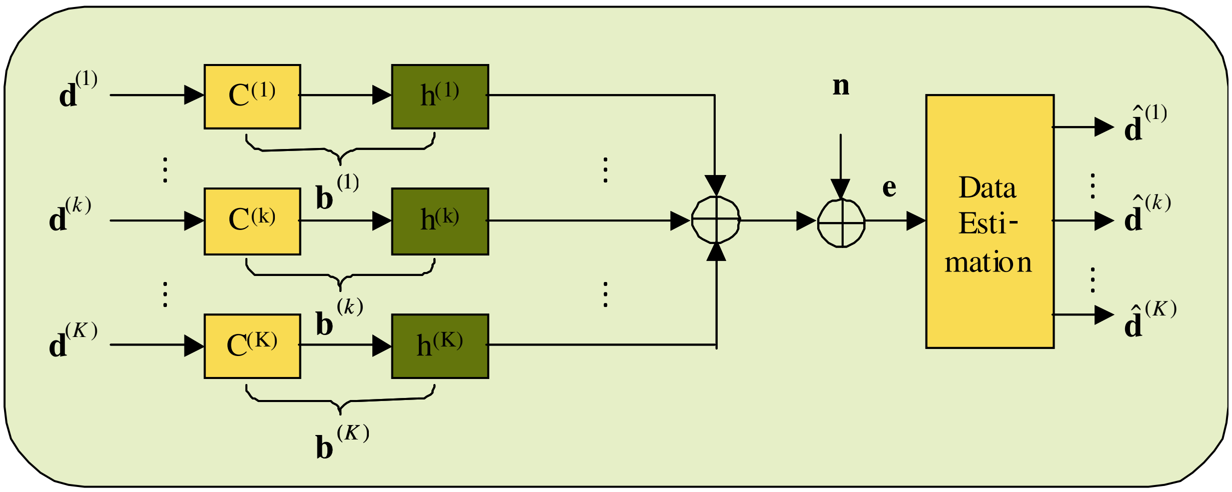


Figure 3-1 Discrete base band model of a TD-SCDMA system.

In the system of Figure 3-1 we assume that there are K_a antennas for the receiver .

The k^{th} user transmits a data symbol sequence block with N symbols:

$$\mathbf{d}^{(k)} = \left(d_1^{(k)}, d_2^{(k)} \ldots d_N^{(k)}\right)^T \qquad \text{k = 1,2,.....,K} \qquad (1)$$

$$\mathbf{d}^{(k)} = \left[d_1^{(1)}, d_1^{(2)}, \ldots d_1^{(k)}, d_2^{(1)}, d_2^{(2)}, \ldots d_2^{(k)}, \ldots, d_N^{(1)}, d_N^{(2)}, \ldots d_N^{(k)}\right]^T \qquad (2)$$

Where N is the number of symbols in each data block.

$$\mathbf{c}^{(k)} = \left(c_1^{(k)} c_2^{(k)} \ldots d_Q^{(k)}\right)^T \qquad \text{k = 1, 2 … K} \qquad (3)$$

$\mathbf{c}^{(k)}$ is the k^{th} user signature, N is the number of symbols in each data block and Q is the spreading factor. All users are assumed to be at the same spreading factor.

Each of the K channels in the system is characterized by its impulse response

$$\mathbf{h}^{(k)} = \left[h_1^{(k)} h_2^{(k)} \ldots h_W^{(k)}\right]^T \qquad \text{k = 1,2 … K} \qquad (4)$$

Where W is the number of taps in the channel.

Similarly, we have the noise vector for antenna k_a

$$\mathbf{n}^{(ka)} = \left[n_1^{(ka)} n_2^{(ka)} \ldots n_{NQ+W-1}^{(ka)} \right]^T \tag{5}$$

and

$$\mathbf{N} = \left[\mathbf{n}^{(1)} \mathbf{n}^{(2)} \ldots \mathbf{n}^{(Ka)} \right]^T \qquad \text{n} = \text{vec}\,[\mathbf{N}] \tag{6}$$

The transmission of the block on N symbols can be modeled by a system of linear equations that relates the spreading codes, the channel's input response and the impact of noise in the signal.

3.2. Received Signal Model

The received sequence received at chip rate from the k_a^{th} antenna is:

$$\boldsymbol{e}^{(ka)} = (e_1^{(ka)}, e_2^{(ka)}, \ldots, e_{NQ+W-1}^{(ka)})^T \tag{7}$$

where Q again is the spreading factor of the data symbol and W is the number of taps in channel.

$$\mathbf{E} = \left[\mathbf{e}^{(1)}, \mathbf{e}^{(2)} \ldots . \mathbf{e}^{(Ka)} \right]^T \qquad \boldsymbol{e} = \text{vec}[\boldsymbol{E}] \tag{8}$$

From Figure 3-1 we can see that

$$\mathbf{b}^{(k,ka)} = \left(b_1^{(k,ka)}, b_2^{(k,ka)}, \ldots b_{Q+W-1}^{(k,ka)} \right)^T = \mathbf{c}(k) * \mathbf{h}^{(k,ka)} \tag{9}$$

Is the convolution of the channel input response with the corresponding spreading code. ($\mathbf{h}^{(k,ka)}$ is the channel impulse response between the user k and antenna k_a, c(k) is the spreading code of the user k.)

Then the we can see that the signal arriving at the receiver can be described by a linear system of equations that relate the user's signal and the receiver input:

$$\mathbf{E} = \mathbf{A}(\mathbf{I}^{(Ka)} \otimes \mathbf{d}) + \mathbf{N} \tag{10}$$

Where, $\otimes$ is the Kronecker product .

Or

$$\mathbf{e} = \mathbf{Ad} + \mathbf{n} \tag{11}$$

The matrix **A** is called channel matrix and is defined as

$$\mathbf{A} = \left[\mathbf{A}^{(1)} \mathbf{A}^{(2)} \ldots \mathbf{A}^{(Ka)} \right]^T \tag{12}$$

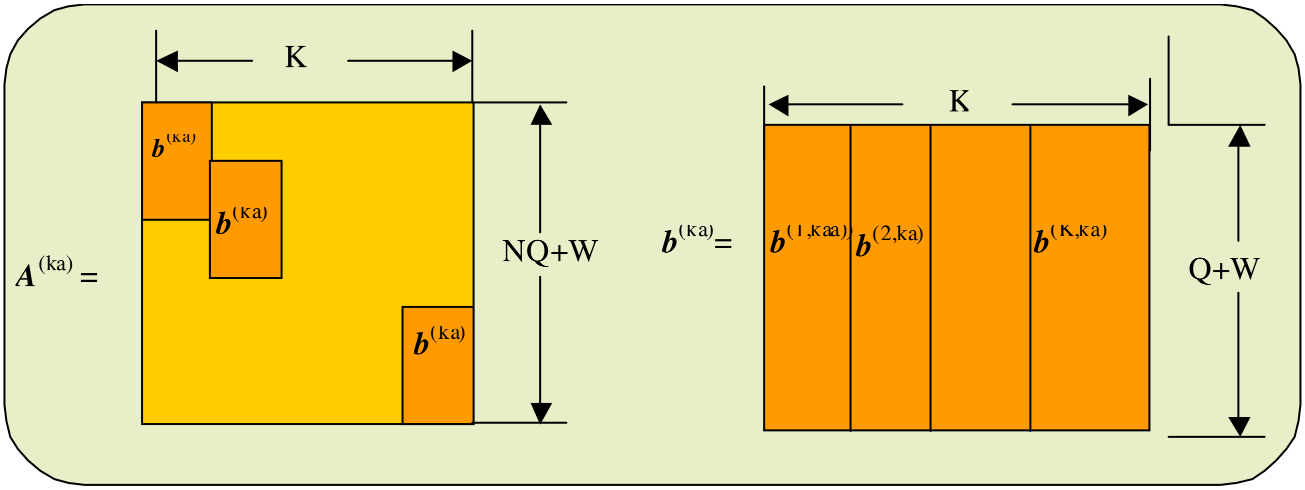


Figure 3-2 The Channel Matrix A

4. Types of Channel Impulse Response

When dealing with spatial-temporal signal processing in the TD-SCDMA, we need to identify two types of channel impulse responses – non-directional channel impulse response and directional channel impulse response.

4.1. Non-Directional Channel Impulse Response.

Let's first discuss the non-directional channel impulse response. The impulse response is defined between each individual user and its antenna. A non-directional channel response between user *k* and antenna *ka* can be modeled as a FIR filter with W taps:

$$\boldsymbol{h}^{(k,ka)} = [h_1^{(k,kd),} h_2^{(k,kd),} \dots , h_W^{(k,kd)}]^T \qquad (13)$$

We can stack all of the channel impulse responses of the k users together to form the non-directional channel impulse response matrix:

$$\mathbf{H}^{(k)} = \begin{bmatrix} \mathrm{h}_1^{(k,1)} & \mathrm{h}_1^{(k,2)} & \dots & \mathrm{h}_1^{(k,Ka)} \\ \mathrm{h}_2^{(k,1)} & \mathrm{h}_2^{(k,2)} & \dots & \mathrm{h}_2^{(k,Ka)} \\ \vdots & \vdots & \vdots & \vdots \\ \mathrm{h}_W^{(k,1)} & \mathrm{h}_W^{(k,2)} & \dots & \mathrm{h}_W^{(k,Ka)} \end{bmatrix} \qquad (14)$$

Then we stack all users' matrixes together to form the system non-directional channel impulse response matrix:

$$\boldsymbol{H} = [\ \boldsymbol{H}^{(1)T},\ \boldsymbol{H}^{(2)T}, \dots\dots,\ \boldsymbol{H}^{(K)T}\ ]$$

4.2. Directional Channel Impulse Response

The second type of channel impulse response is the *directional channel impulse response*. The directional channel impulse response is directly related to each signal path with a DoA and it is defined to be the channel impulse response between user k and a reference point:

$$\boldsymbol{h}_d^{(k,kd)} = [h_{d1}^{(k,kd),} h_{d2}^{(k,kd),} \dots , h_{dW}^{(k,kd)}]^T$$

Similarly as with the non-directional channel impulse response matrix, we have:

$$\mathbf{H}_d^{(k)} = \begin{bmatrix} \mathrm{h}_{d1}^{(k,1)} & \mathrm{h}_{d1}^{(k,2)} & \dots & \mathrm{h}_{d1}^{(k,Kd(k))} \\ \mathrm{h}_{d2}^{(k,1)} & \mathrm{h}_{d2}^{(k,2)} & \dots & \mathrm{h}_{d2}^{(k,Kd(k))} \\ \vdots & \vdots & \vdots & \vdots \\ \mathrm{h}_{dW}^{(k,1)} & \mathrm{h}_{dW}^{(k,2)} & \dots & \mathrm{h}_{dW}^{(k,Kd(k))} \end{bmatrix} \qquad (15)$$

Where $K_d(k)$ is the number of DoA paths of the k^{th} user.

$$\boldsymbol{H}_d = [\ \boldsymbol{H}_d^{(1)},\ \boldsymbol{H}_d^{(2)},\ldots\ldots,\ \boldsymbol{H}_d^{(K)}] \tag{16}$$

(Note that there is no transpose operation)

There is a close link between the non-directional channel impulse response and the directional channel impulse response. The non-directional channel impulse response for a given user *k* and given antenna k_a is the summation of all directional channel impulse responses of the user k on the antenna k_a:

$$\boldsymbol{h}^{(\mathrm{k,ka})} = \sum_{kd=1}^{Kd(k)} e^{j\phi(k,ka,kd)} \boldsymbol{h}_d^{(k,kd)} \tag{17}$$

where $\phi(\mathrm{k,ka,kd}) = \{2\pi L^{(ka)}\cos(\beta^{(k,kd)} - \alpha^{(ka)})\}/\lambda$ k=1…K $k_a = 1\ldots K_a$ and $k_d = 1\ldots K_d^{(k)}$;

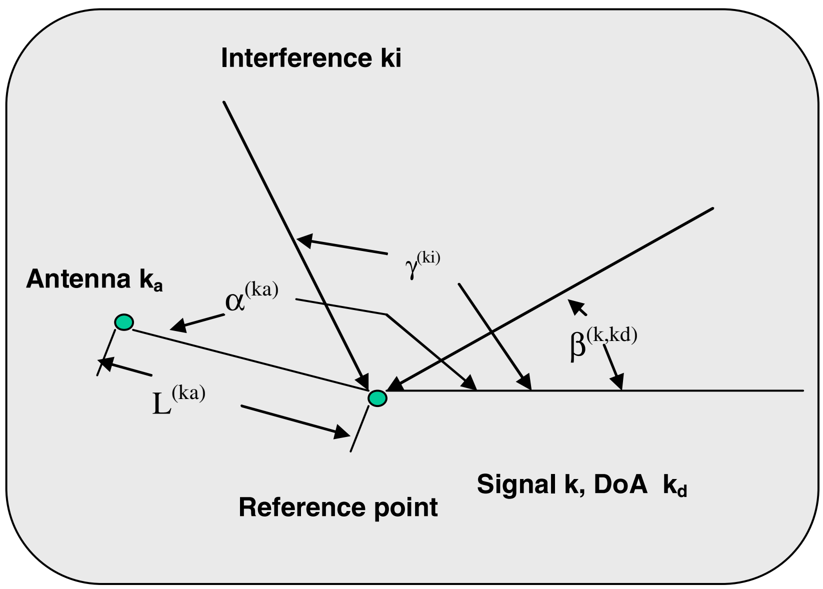


Figure 4-1 Antenna array model

For a given user k and DoA k_d , $e^{j\phi(k,ka,kd)}$ (ka = 1….Ka) forms its steering vector. Thus we define:

$$\boldsymbol{A}^{(k)} = [\ \boldsymbol{a}^{(k,1)},\ \boldsymbol{a}^{(k,2)},\ldots\ldots,\ \boldsymbol{a}^{(k,Kd(k))}] \qquad k=1\ldots,K \tag{18}$$

as the user k^{th} user's steering matrix. Then the relation between the directional channel impulse response and non-directional channel impulse response is given by

$$\boldsymbol{H}^{(k)} = \sum_{kd=1}^{Kd(k)} \boldsymbol{h}_d^{(k,kd)} \boldsymbol{a}^{(k,kd)T} = \boldsymbol{H}_d^{(k)} \boldsymbol{A}^{(k)T} \tag{19}$$

5. Non-directional channel impulse response

We will estimate the non-directional channel impulse response first. The estimated response can be used to estimate the DoA for each user and each path. Then based on the estimated DoA and non-directional channel impulse response, the directional channel impulse response can be derived. The estimation will be based on the midamble training sequence with length of W+L., where W is the maximum number of channel delay taps.

Suppose we have $\boldsymbol{x} = \boldsymbol{Ad} + \boldsymbol{n}$, where $\boldsymbol{n}$ is a Nx1 Gaussian noise vector (it is not necessary to be white), $\boldsymbol{A}$ is an Nxp known matrix, $\boldsymbol{d}$ is px1 signal vector and $\boldsymbol{x}$ is Nx1 observed signal, then a ML estimator of $\boldsymbol{d}$ can be derived as

$$\hat{\mathbf{d}} = (\mathbf{A}^{\mathrm{H}}\mathbf{R}_n^{-1}\mathbf{A})\mathbf{A}^{\mathrm{H}}\mathbf{R}_n^{-1}x \tag{20}$$

Actually, the estimator $\hat{\mathbf{d}}$ is an efficient MVU (Minimum Variance Unbiased estimator reaching the Cramer-Rao Lower Bound) if the vector $\boldsymbol{n}$ is a complex Gaussian noise vector.

Now, we define *Ka Lx1* column vectors: $\boldsymbol{e}_m^{(ka)}$ *for ka=1…Ka.* $\boldsymbol{e}_m^{(ka)}$ is the received signal for the antenna k_a based on the last *L* midamble training sequence. Stack Ka vectors together to form the received *L x Ka* matrix

$$\boldsymbol{E}_{\mathrm{m}} = [\boldsymbol{e}_{\mathrm{m}}^{(1)}, \boldsymbol{e}_{\mathrm{m}}^{(2)}, \ldots, \boldsymbol{e}_{\mathrm{m}}^{(\mathrm{Ka})}]$$

Similarly, we define received noise vectors and $\mathrm{LxK_a}$ matrix

$$\boldsymbol{N}_{\mathrm{m}} = [\boldsymbol{n}_{\mathrm{m}}^{(1)}, \boldsymbol{n}_{\mathrm{m}}^{(2)}, \ldots, \boldsymbol{n}_{\mathrm{m}}^{(\mathrm{Ka})}]$$

Then we have

$$\boldsymbol{E}_{\mathrm{m}} = \boldsymbol{GH} + \boldsymbol{N}_{\mathrm{m}}$$

where the matrix **G** is an *L x KW* observing matrix.

Moreover we have

$$\begin{aligned}\boldsymbol{e}_{\mathrm{m}} &= \mathrm{vec}\{\boldsymbol{E}_{\mathrm{m}}\} = \mathrm{vec}\{\boldsymbol{GH}\} + \mathrm{vec}\{\boldsymbol{N}_{\mathrm{m}}\} = \mathrm{vec}\{\boldsymbol{GHI}^{(\mathrm{Ka})}\} + \boldsymbol{n}_{\mathrm{m}} \\ &= (\boldsymbol{I}^{(\mathrm{Ka})} \otimes \boldsymbol{G})\mathrm{vec}\{\boldsymbol{H}\} + \boldsymbol{n}_{\mathrm{m}} = (\boldsymbol{I}^{(\mathrm{Ka})} \otimes \boldsymbol{G})\boldsymbol{h} + \boldsymbol{n}_{\mathrm{m}}\end{aligned} \tag{21}$$

where $\mathbf{I}^{(\mathrm{Ka})}$ is a K_a-*by*-K_a identity matrix, and $\otimes$ is the Kronecker product operator.

Thus, from (8), we have

$$\hat{\mathbf{h}} = \{(\mathbf{I}^{(ka)} \otimes \mathbf{G})^H \mathbf{R}_m^{-1}(\mathbf{I}^{(ka)} \otimes \mathbf{G})\}^{-1}(\mathbf{I}^{(ka)} \otimes \mathbf{G})^H \mathbf{R}_m^{-1}\mathbf{e}_m \tag{22}$$

Now we have to work out the matrix **G** and the noise covariance matrix $\mathbf{R}_{\mathrm{m}}$ before the non-directional channel impulse response vector **h** can be obtained.

We define the matrix **G** to be

$$\boldsymbol{G} = [\boldsymbol{G}^{(1)}, \boldsymbol{G}^{(2)}, \ldots, \boldsymbol{G}^{(\mathrm{K})}] \tag{23}$$

where $\mathbf{G}^{(k)}$ k=1…K is the LxW Toeplitz matrix of the midamble training sequence for the kth user. It is clear that the matrix G is pre-defined since it is composed from the given midamble training code for all K users.

For the noise covariance matrix $\mathbf{R}_{\mathrm{m}}$, we have

$$\mathbf{R}_m = \begin{bmatrix} \mathbf{R}_m^{(1,1)} & \mathbf{R}_m^{(1,2)} & \cdots & \mathbf{R}_m^{(1,Ka)} \\ \mathbf{R}_m^{(2,1)} & \mathbf{R}_m^{(2,2)} & \cdots & \mathbf{R}_m^{(2,Ka)} \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{R}_m^{(Ka,1)} & \mathbf{R}_m^{(Ka,2)} & \cdots & \mathbf{R}_m^{(Ka,Ka)} \end{bmatrix} \tag{24}$$

In (24), we have $\boldsymbol{R}_m^{(i,j)} = E\{ \boldsymbol{n}_m^{(i)} \boldsymbol{n}_m^{(j)H} \}$

$$= E\{\sum_{ki=1}^{Ki} \boldsymbol{e}^{j\phi(ki,i)} \boldsymbol{n}_d^{(ki)} \sum_{kj=1}^{Ki} \boldsymbol{e}^{-j\phi(kj,j)} \boldsymbol{n}_d^{(kj)H} \}$$

$$= E\{\sum_{ki=1}^{Ki} \boldsymbol{e}^{j[\phi(ki,i)-\phi(ki,j)]} \boldsymbol{n}_d^{(ki)} \boldsymbol{n}_d^{(ki)H} \}$$

$$= \sum_{ki=1}^{Ki} \boldsymbol{e}^{j[\phi(ki,i)-\phi(ki,j)]} \tilde{\boldsymbol{R}}_m^{(ki)} \sigma^{(ki)2}$$

where $\tilde{\mathbf{R}}_m^{(ki)} = E\{\mathbf{n}_d^{(ki)} \mathbf{n}_d^{(ki)H}\} / \sigma^{(ki)2}$. Notice that $\tilde{\mathbf{R}}_m^{(ki)}$ is the same for all Ki, Then let

$\tilde{\mathbf{R}}_m = \tilde{\mathbf{R}}_m^{(ki)}$ for all ki=1….Ki and $r_{i,j} = r_{i,j}^{*} = \sum_{ki=1}^{Ki} (\sigma^{(ki)2}) \mathbf{e}^{j[\phi(ki,i)-\phi(ki,j)]}$

we have

$\boldsymbol{R}_m^{(i,j)} = r_{i,j} \tilde{\boldsymbol{R}}_m$ for i,j = 1…..K_a and

$$\mathbf{R}_m = \mathbf{R}_d \otimes \tilde{\mathbf{R}}_m \tag{25}$$

where $[\mathbf{R}_d]_{i,j} = r_{i,j}$

The matrix $\tilde{\mathbf{R}}_m$ is a temporal covariance matrix and $\mathbf{R}_d$ is spatial covariance matrix.

From (10)

$$\hat{\mathbf{h}} = \{(\mathbf{I}^{(ka)} \otimes \mathbf{G})^H \mathbf{R}_m^{-1} (\mathbf{I}^{(ka)} \otimes \mathbf{G})\}^{-1} (\mathbf{I}^{(ka)} \otimes \mathbf{G})^H \mathbf{R}_m^{-1} \mathbf{e}_m$$

since

$$(\boldsymbol{I}^{(ka)} \otimes \boldsymbol{G})^H \boldsymbol{R}_m^{-1} = (\boldsymbol{I}^{(ka)} \otimes \boldsymbol{G})^H (\boldsymbol{R}_d^{-1} \otimes \tilde{\boldsymbol{R}}_m^{-1})$$

$$= \boldsymbol{R}_d^{-1} \otimes \underline{\boldsymbol{G}}^H \tilde{\boldsymbol{R}}_m^{-1}$$

$$\begin{aligned}\hat{\boldsymbol{h}} &= \{\ \boldsymbol{R}_{\mathrm{d}}^{-1} \otimes \boldsymbol{G}^{\mathrm{H}}\tilde{\boldsymbol{R}}_m^{-1}\boldsymbol{G}\}^{-1}(\boldsymbol{R}_{\mathrm{d}}^{-1} \otimes \boldsymbol{G}^{\mathrm{H}}\tilde{\boldsymbol{R}}_m^{-1})\boldsymbol{e}_{\mathrm{m}} \\ &= \{\boldsymbol{R}_{\mathrm{d}} \otimes (\boldsymbol{G}^{\mathrm{H}}\tilde{\boldsymbol{R}}_m^{-1}\boldsymbol{G})^{-1}\}(\boldsymbol{R}_{\mathrm{d}}^{-1} \otimes \boldsymbol{G}^{\mathrm{H}}\tilde{\boldsymbol{R}}_m^{-1})\boldsymbol{e}_{\mathrm{m}} \\ &= \{\boldsymbol{I}^{(\mathrm{ka})} \otimes (\boldsymbol{G}^{\mathrm{H}}\tilde{\boldsymbol{R}}_m^{-1}\boldsymbol{G})^{-1}\boldsymbol{G}^{\mathrm{H}}\tilde{\boldsymbol{R}}_m^{-1}\}\boldsymbol{e}_{\mathrm{m}} \\ &= \{\boldsymbol{I}^{(\mathrm{ka})} \otimes \boldsymbol{M}_{\mathrm{m}}\}\boldsymbol{e}_{\mathrm{m}}\end{aligned}$$

Where

$$M_m = (G^H\,\tilde{\mathbf{R}}_m^{-1}\,\mathbf{G})^{-1}\mathbf{G}^H\,\tilde{\mathbf{R}}_m^{-1}$$

If $\tilde{\mathbf{R}}_m = 1$ then $M_m = \left(G^H G\right)^{-1} G^H$

6. Directional channel impulse response

The directional channel impulse response is based on each directional signal path. It is the impulse response between a given directional signal path and reference point. Based on (7)

$$\boldsymbol{H}^{(k)} = \sum_{kd=1}^{Kd(k)} \boldsymbol{h}_{\mathrm{d}}^{(k,kd)} \boldsymbol{a}^{(k,kd)T} = \boldsymbol{H}_{d}^{(k)} \boldsymbol{A}^{(k)T}$$

if $\boldsymbol{H}^{(k)}$ and $\boldsymbol{A}^{(k)T}$ can be obtained or estimated, then $\boldsymbol{H}_{\mathrm{d}}^{(k)}$ can be derived.

From

$$\boldsymbol{e}_{\mathrm{m}} = \mathrm{vec}\{\boldsymbol{G}\,\boldsymbol{H}\} + \boldsymbol{n}_{\mathrm{m}} = \boldsymbol{G}_{\mathrm{d}}\boldsymbol{h}_{\mathrm{d}} + \boldsymbol{n}_{\mathrm{m}}$$

we have the ML estimator of $\boldsymbol{h}_{\mathrm{d}}$

$$\hat{\mathbf{h}}_{d} = (\mathbf{G}_{d}{}^{H}(\mathbf{R}_{d} \otimes \tilde{\mathbf{R}}_{m})^{-1}\mathbf{G}_{d})^{-1}\mathbf{G}_{d}{}^{H}(\mathbf{R}_{d} \otimes \tilde{\mathbf{R}}_{m})^{-1}\mathbf{e}_{m}$$

where $\mathbf{X}_{m}{}^{-1} = (\mathbf{G}_{d}{}^{H}(\mathbf{R}_{d} \otimes \tilde{\mathbf{R}}_{m})^{-1}\mathbf{G}_{d})^{-1}$ is the decorrelator filter and $\boldsymbol{G}_{d}{}^{H}(\boldsymbol{R}_{d} @ \tilde{\boldsymbol{R}}_{m})^{-1}$ is the spatial-temporal whitening matched filter and

$$\mathbf{G}_{d}{}^{H}(\mathbf{R}_{d} \otimes \mathbf{R}_{m})^{-1} = \begin{bmatrix} \left(\mathbf{A}^{(1)\mathbf{H}} \otimes \mathbf{G}^{(1)\mathbf{H}}\right) \otimes \left(\mathbf{R}_{d}{}^{-1} \otimes \tilde{\mathbf{R}}_{m}{}^{-1}\right) \\ \vdots \\ \left(\mathbf{A}^{(K)\mathbf{H}} \otimes \mathbf{G}^{(K)\mathbf{H}}\right) \otimes \left(\mathbf{R}_{d}{}^{-1} \otimes \tilde{\mathbf{R}}_{m}{}^{-1}\right) \end{bmatrix} = \begin{bmatrix} \left(\mathbf{A}^{(1)\mathbf{H}}\mathbf{R}_{d}{}^{-1} \otimes \mathbf{G}^{(1)H}\tilde{\mathbf{R}}_{m}{}^{-1}\right) \\ \vdots \\ \left(\mathbf{A}^{(1)\mathbf{H}}\mathbf{R}_{d}{}^{-1} \otimes \mathbf{G}^{(1)H}\tilde{\mathbf{R}}_{m}{}^{-1}\right) \end{bmatrix}$$

Then we have

$$\boldsymbol{G}_{\mathrm{d}}{}^{\mathrm{H}}(\boldsymbol{R}_{\mathrm{d}} \otimes \boldsymbol{R}_{\mathrm{m}})^{-1}\,\mathrm{vec}\{\boldsymbol{E}_{\mathrm{m}}\} = \boxed{\begin{matrix} \mathrm{Vec}\{\underset{\sim}{\boldsymbol{G}}^{(1)\mathrm{H}}\boldsymbol{R}_{\mathrm{m}}{}^{-1}\boldsymbol{E}_{\mathrm{m}}(\boldsymbol{R}_{\mathrm{d}}{}^{-1})^{*}\boldsymbol{A}^{(1)*}\} \\ \mathrm{Vec}\{\boldsymbol{G}^{(2)\mathrm{H}}\boldsymbol{R}_{\mathrm{m}}{}^{-1}\boldsymbol{E}_{\mathrm{m}}(\boldsymbol{R}_{\mathrm{d}}{}^{-1})^{*}\boldsymbol{A}^{(2)*}\} \\ \\ \mathrm{Vec}\{\boldsymbol{G}^{(\mathrm{K})\mathrm{H}}\boldsymbol{R}_{\mathrm{m}}{}^{-1}\boldsymbol{E}_{\mathrm{m}}(\boldsymbol{R}_{\mathrm{d}}{}^{-1})^{*}\boldsymbol{A}^{(\mathrm{K})*}\} \end{matrix}}$$

Where $\boldsymbol{G}^{(k)\mathrm{H}}\boldsymbol{R}_{\mathrm{m}}{}^{-1}$ is the temporal whitening matched filter and $(\boldsymbol{R}_{\mathrm{d}}{}^{-1})^{*}\boldsymbol{A}^{(k)*}$ is the spatial whitening matched filter of the user k.

We define the spatial whitening matched filter

$\boldsymbol{W}^{(k)} = (\boldsymbol{R}_{\mathrm{d}}{}^{-1})^{*}\boldsymbol{A}^{(k)*} = [\,\boldsymbol{w}^{(k,1)}, \boldsymbol{w}^{(k,2)}, \ldots\ldots, \boldsymbol{w}^{(k,Kd(k))}]$, thus $\boldsymbol{w}^{(k,kd)}$ is beanformed for the k_d's DoA.

7. Estimation of transmitted data

Based on the directional channel impulse response, we will estimate the transmitted data. As we will see, beam-forming will be generated for each DoA path and all the DoA paths of the same user will be coherently combined to enhance the system's performance.

We define vector $\boldsymbol{d}$ as the transmitted data column vector of length KN for all K users;

$\boldsymbol{d} = [\boldsymbol{d}^{(1)T}, \boldsymbol{d}^{(2)T}, \ldots\ldots, \boldsymbol{d}^{(K)T}]^T$ where $\boldsymbol{d}^{(k)T}$ is user k's transmitted data vector of length N

Define matrix $\boldsymbol{E}$ the received signal matrix with dimension (NQ+W-1) x K_a:

$\boldsymbol{E} = [\ \boldsymbol{e}^{(1)}, \boldsymbol{e}^{(2)}, \ldots\ldots, \boldsymbol{e}^{(Ka)}]$, where $\boldsymbol{e}^{(ka)}$ is the received signal vector of length NQ+W-1 from antenna ka. And we also define $\boldsymbol{e} = \mathrm{vec}\{\boldsymbol{E}\}$ and the combined noise vector

$\boldsymbol{n} = [\boldsymbol{n}^{(1)T}, \boldsymbol{n}^{(2)T}, \ldots\ldots, \boldsymbol{n}^{(K)T}]^T$ of length $(NQ+W-1)K_a$:

The data $\boldsymbol{d}$ has to been spreaded by the special signature code before it can be transmitted, thus we define the spreading signature code matrix for user k:

$\boldsymbol{C}^{(k)} = \boldsymbol{I}^{(N)} \otimes \boldsymbol{c}^{(k)} =$

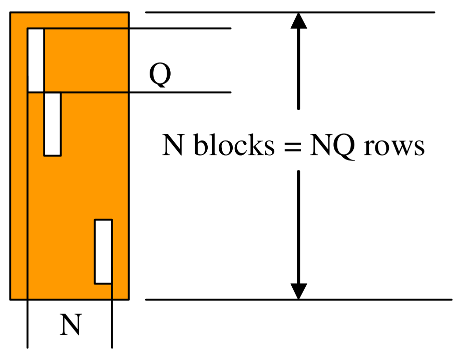


Figure 7-1 Structure of the Spreading signature code matrix

Where $\boldsymbol{c}^{(k)}$ is the special signature code for user k, k=1…K. Stack all $\boldsymbol{C}^{(k)}$ k=1…K together to form the combined signature code matrix

$\boldsymbol{C} = \mathrm{blockdiag}[\ \boldsymbol{C}^{(1)}, \boldsymbol{C}^{(2)}, \ldots\ldots, \boldsymbol{C}^{(K)}\ ]$

The spreaded data can be written as:

$\boldsymbol{C}\,\boldsymbol{d} = \mathrm{blockdiag}[\ \boldsymbol{C}^{(1)}, \boldsymbol{C}^{(2)}, \ldots\ldots, \boldsymbol{C}^{(K)}\ ]\,[\boldsymbol{d}^{(1)T}, \boldsymbol{d}^{(2)T}, \ldots\ldots, \boldsymbol{d}^{(K)T}]^T$

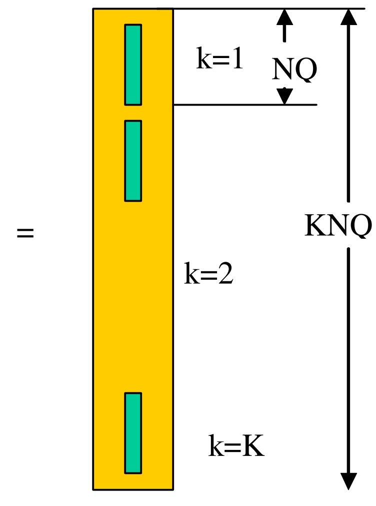


Figure 7-2 Structure of Vector Cd

The received signal vector $\boldsymbol{e}$ is the transmitted spreaded data pass the directional channel plus the noise:

$$\boldsymbol{e} = \boldsymbol{A}_d\, \boldsymbol{H}_{da}\, \boldsymbol{C}\, \boldsymbol{d} + \boldsymbol{n}$$

Where $\boldsymbol{A}_d = \boldsymbol{A} \otimes \boldsymbol{I}^{(NQ+W-1)}$, $\boldsymbol{A}=[\boldsymbol{A}^{(1)}, \boldsymbol{A}^{(2)},\ldots\ldots, \boldsymbol{A}^{(K)}]$ and

$$\boldsymbol{H}_{da} = \text{blockdiag}[\, \boldsymbol{H}_{da}^{(1)} , \boldsymbol{H}_{da}^{(2)} ,\ldots.., \boldsymbol{H}_{da}^{(K)} \,]$$

$$\mathbf{H}_{da}^{(k)} = \begin{bmatrix} \mathbf{H}_{da}^{(k,1)} \\ \mathbf{H}_{da}^{(k,2)} \\ \vdots \\ \mathbf{H}_{da}^{(k,Kd(k))} \end{bmatrix}$$

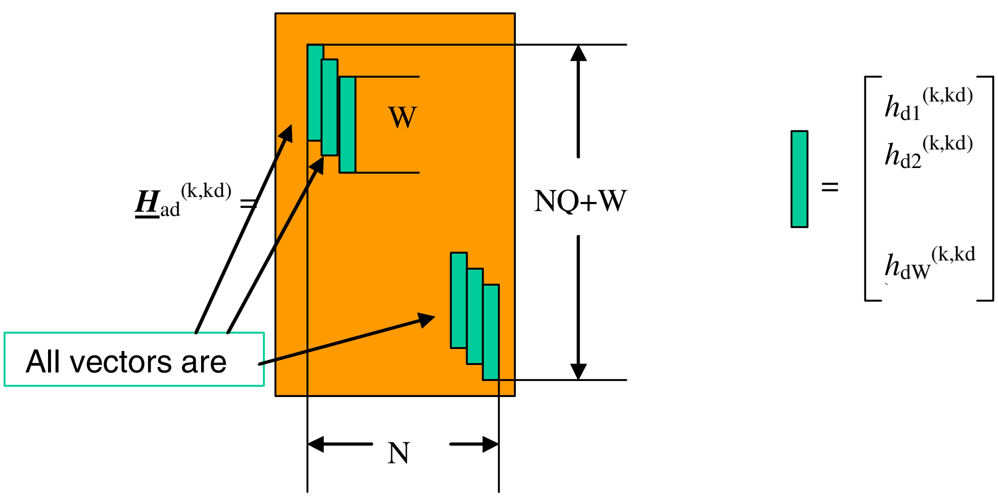


Figure 7-3 The structure of matrix $H_{da}^{(k,kd)}$

Then based on the ML rule, we can estimate transmitted data:

$$\hat{\boldsymbol{d}} = (\, \boldsymbol{C}^{H}\boldsymbol{H}_{da}^{H}\boldsymbol{A}_{d}^{H}(\boldsymbol{R}_{d}^{-1} \otimes \tilde{\boldsymbol{R}}_{n}^{-1})\boldsymbol{A}_{d}\boldsymbol{H}_{da}\boldsymbol{C})^{-1}\, \boldsymbol{C}^{H}\boldsymbol{H}_{da}^{H}\boldsymbol{A}_{d}^{H}(\boldsymbol{R}_{d}^{-1} \otimes \tilde{\boldsymbol{R}}_{n}^{-1})\, \boldsymbol{e}$$

$$= \boldsymbol{X}\,\boldsymbol{C}^{H}\boldsymbol{H}_{da}^{H}\boldsymbol{A}_{d}^{H}(\boldsymbol{R}_{d}^{-1} \otimes \tilde{\boldsymbol{R}}_{n}^{-1})\boldsymbol{e}$$

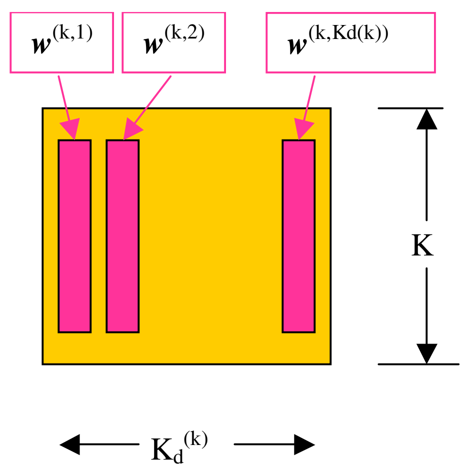
where $\boldsymbol{X} = (\, \boldsymbol{C}^{H}\boldsymbol{H}_{da}^{H}\boldsymbol{A}_{d}^{H}(\boldsymbol{R}_{d}^{-1} \otimes \tilde{\boldsymbol{R}}_{n}^{-1})\boldsymbol{A}_{d}\boldsymbol{H}_{da}\boldsymbol{C})^{-1}$ is a zero force equalizer.

Since $\boldsymbol{A}_{d}^{H}(\boldsymbol{R}_{d}^{-1} \otimes \tilde{\boldsymbol{R}}_{n}^{-1}) = (\, \boldsymbol{A}^{H} \otimes \boldsymbol{I}^{(NQ+W-1)}\,)\,(\boldsymbol{R}_{d}^{-1} \otimes \tilde{\boldsymbol{R}}_{n}^{-1}) = \boldsymbol{A}^{H}\,\boldsymbol{R}_{d}^{-1} \otimes \tilde{\boldsymbol{R}}_{n}^{-1}$

$$\hat{\boldsymbol{d}} = \boldsymbol{X}\,\boldsymbol{C}^{H}\boldsymbol{H}_{da}^{H}\,(\boldsymbol{A}^{H}\,\boldsymbol{R}_{d}^{-1} \otimes \tilde{\boldsymbol{R}}_{n}^{-1})\mathrm{vec}\{\boldsymbol{E}\} = \boldsymbol{X}\,\boldsymbol{C}^{H}\boldsymbol{H}_{da}^{H}\,\mathrm{vec}\{\tilde{\boldsymbol{R}}_{n}^{-1}\,\boldsymbol{E}\,(\boldsymbol{R}_{d}^{-1})^{T}\boldsymbol{A}^{*}\}$$

We define

$$\boldsymbol{W}^{(k)} = (\boldsymbol{R}_{d}^{-1})^{T}\boldsymbol{A}^{(k)*} =$$



As the weight matrix for the user k and
$\boldsymbol{W} = (\boldsymbol{R}_{d}^{-1})^{T}\boldsymbol{A}^{*} = [\, \boldsymbol{w}^{(1,1)}, \ldots, \boldsymbol{w}^{(1,Kd(1))}, \ldots\ldots, \boldsymbol{w}^{(K,1)}, \ldots, \boldsymbol{w}^{(K,Kd(K))}]$ is the combined antenna weight matrix for all K users. Then the combined beam output is

$$\boldsymbol{Z} = \boldsymbol{E}\boldsymbol{W} = [\boldsymbol{y}^{(1,1)}, \ldots, \boldsymbol{y}^{(1,Kd(1))}, \ldots\ldots, \boldsymbol{y}^{(K,1)}, \ldots, \boldsymbol{y}^{(K,Kd(K))}], \text{ where } \quad \boldsymbol{y}^{(k,kd)} = \boldsymbol{E}\boldsymbol{w}^{(k,kd)}$$

$$\hat{\boldsymbol{d}} = \boldsymbol{X}\,\boldsymbol{C}^{H}\boldsymbol{H}_{da}^{H}\,(\boldsymbol{A}^{H}\,\boldsymbol{R}_{d}^{-1} \otimes \tilde{\boldsymbol{R}}_{n}^{-1})\mathrm{vec}\{\boldsymbol{E}\} = \boldsymbol{X}\,\boldsymbol{C}^{H}\boldsymbol{H}_{da}^{H}\,\mathrm{vec}\{\tilde{\boldsymbol{R}}_{n}^{-1}\,\underline{\boldsymbol{E}}\,\underline{\boldsymbol{W}}\,\}$$

$$= \boldsymbol{X}\,\boldsymbol{C}^{H}\boldsymbol{H}_{da}^{H}\,\mathrm{vec}\{\tilde{\boldsymbol{R}}_{n}^{-1}\,\underline{\boldsymbol{Z}}\,\}$$

Since $\mathrm{vec}\{\tilde{\boldsymbol{R}}_{n}^{-1}\,\boldsymbol{Z}\,\} = \mathrm{vec}\{\tilde{\boldsymbol{R}}_{n}^{-1}\,\boldsymbol{Z}\,\boldsymbol{I}^{(Kd)}\,\} = (\,\boldsymbol{I}^{(Kd)} \otimes \tilde{\boldsymbol{R}}_{n}^{-1})\mathrm{vec}\{\boldsymbol{Z}\}$, then

$$\hat{\boldsymbol{d}} = \boldsymbol{X}\,\boldsymbol{C}^{H}\boldsymbol{H}_{da}^{H}(\,\boldsymbol{I}^{(Kd)} \otimes \tilde{\boldsymbol{R}}_{n}^{-1})\mathrm{vec}\{\boldsymbol{Z}\}$$

is the estimate of the transmitted data.

$$= \boldsymbol{X}\,\boldsymbol{C}^{H}\boldsymbol{H}_{da}^{H}(\,\boldsymbol{I}^{(Kd)} \otimes \tilde{\boldsymbol{R}}_{n}^{-1})\,[\boldsymbol{y}^{(1,1)T}, \ldots, \boldsymbol{y}^{(1,Kd(1))T}, \ldots\ldots, \boldsymbol{y}^{(K,1)T}, \ldots, \boldsymbol{y}^{(K,Kd(K))T}]$$

8. Summary

In this paper, the spatial-temporal processing of a received TD-SCDMA signal is presented. The directional channel impulse response is estimated based on the non-directional response. It is shown in this paper that the ML estimator of the transmitted data utilizes both the temporal and spatial information of the signal and that the estimator consists of a bean former followed by a zero-force equalizer.

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